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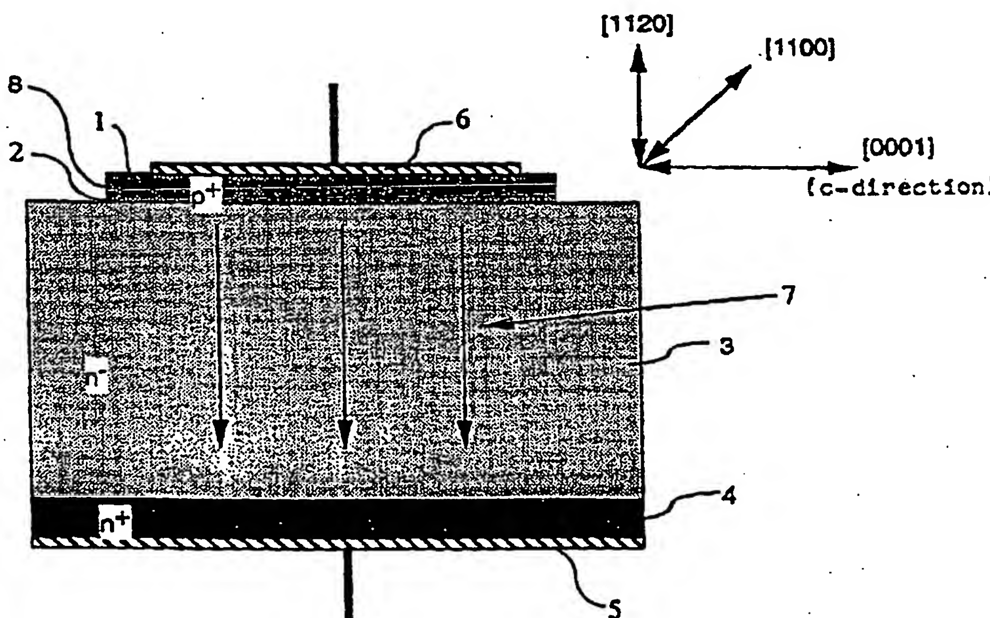

(57) Abstract

The present invention relates to a semiconductor device comprising at least one pn-junction (2) in which both a p-conducting layer (1) and an n-conducting layer (3) of the pn-junction (2) are in the form of doped layers of silicon carbide (SiC) and in which one of these layers consists of a voltage-absorbing layer (3) with low doping concentration, wherein at least the voltage-absorbing layer (3) of the pn-junction (2) exhibits a crystal structure in 6H-SiC where the [0001]-direction of the SiC crystal is oriented so that it deviates from the main current direction (7) in a current flowing through the crystal when the device is in conducting state. The conducting ability of the device is thus improved when it is in conducting state.

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Semiconductor device in silicon carbide

TECHNICAL FIELD

The present invention relates to a semiconductor device with silicon carbide as base material, in which the silicon carbide material consists of one of the poly-types having anisotropic electrical properties (e.g. 6H) and in which the semiconductor device is oriented at an angle in relation to the crystal structure of the silicon carbide material in order to ensure optimum properties.

BACKGROUND ART

Semiconductor devices with silicon carbide (SiC) as base material are under continuous development for use in high-temperature contexts, high-power applications and under conditions with high radiation. Conventional semiconductors are unable to function satisfactorily under such circumstances. Estimates indicate that SiC transistors of power MOSFET type and diode rectifiers of SiC would be able to operate over large voltage and temperature ranges and exhibit better breaker properties, while still remaining 20 times smaller in volume that corresponding silicon devices. The basis of these improvements lies in the built-in advantageous material properties of silicon carbide in comparison with silicon, such as a higher break-through field (more than 5 times that of silicon) a higher thermal conducting ability (more than 3 times that of silicon) and a higher energy band gap (2.9 eV for 6H-SiC, one of the crystal structures for SiC), thereby permitting higher working temperatures at the junctions.

Since the silicon carbide semiconductor technology is relatively young and not optimized, there are many production problems that require a solution before fully usable SiC power semiconductors can be realized experimentally and production can be carried out on a larger scale. Difficulties requiring a solution are that the background doping concentration for the voltage-absorbing layer in the device must be reduced if a single device is to be able to withstand voltages of several kilovolt, that the surface-passification technology for silicon carbide

must be optimized and that the amount of critical defects in the silicon carbide material must be reduced if, for instance, it is to be possible to manufacture high-current devices of large area. Other areas requiring development are, for instance, methods of producing good ohmic contacts to the material, methods of doping with e.g. implantation, process techniques for etching, etc.

High-volt diodes in 6H-SiC with epitaxially created pn-junctions and Schottky junctions have been produced experimentally (M. Bhatnagar and B. J. Baliga, IEEE Trans. Electron Devices, vol. 40, No. 3, pages 645-655, March 1993). Some of the problems listed above, such as a decrease in the doping concentration, have thus already been solved and the first 2000 V silicon carbide rectifiers ever have been reported. Other power devices, e.g. MOSFET, MESFET and thyristors, have also been manufactured experimentally (see for instance a survey in J. W. Palmour et al, Proc of the MRS Spring Meeting, San Francisco, April 1994).

Silicon carbide can exist in a number of different crystal structures, so-called poly-types, of which the cubic shape 3C and the hexagonal shapes 4H and 6H are those considered to be the most interesting for power devices. Of these 6H-SiC has become the one most commonly used since this poly-type is the first to be produced commercially.

A special property of 6H-SiC is its anisotropic electrical properties. In this hexagonal structure the crystallographic [0001]-direction is defined as the "c-direction". Both the crystal directions [1120] and [1100] are located in the base plane of the crystal. It has been shown that the electron mobility in the [0001]-direction is five times lower than in the other directions (see, for instance, W. J. Schaffer et al, Proc of the MRS Spring Meeting, San Francisco, April 1994). However, as far as has been ascertained, the hole mobility does not exhibit any anisotropy. Said anisotropy does not appear to exist in the 4H-SiC structure.

The semiconductor devices manufactured experimentally from silicon carbide, in 6H material for instance, have been produced on material manufactured with epitaxy (e.g. CVD) where the growth of the

epitaxial layers has occurred in the c-direction. The main current direction in the device is thus parallel to the c-direction. A drawback with such known devices is that the main current direction is oriented in the direction having the least mobility, i.e. along the c-direction of the crystal which gives, for instance, higher conducting voltage than if a direction in the crystal having a higher mobility were to be used for current conducting.

DESCRIPTION OF THE INVENTION:

The invention constitutes a semiconductor device comprising one or more pn-junctions in which both the p-conducting layer(s) and the n-conducting layer(s) are in the form of doped layers of silicon carbide (SiC) with anisotropic electrical properties. Alternatively at least one of the layers is made of silicon carbide having anisotropic electrical properties. The device consists of a substrate with high doping concentration (p- or n-doped) on which several layers of varying doping are applied (e.g. epitaxially using CVD technology). At least one of the layers has low doping concentration and constitutes the voltage-absorbing layer in the device. The doping level and thickness of this layer determine the voltage that can be absorbed by the component.

In a diode, for instance, if the substrate is of n-type it may constitute the cathode, the voltage-absorbing layer with low doping concentration may be n-doped and, on top of this, a highly-doped p-layer may constitute the anode. The electric current in the component passes between anode and cathode when the device is conducting.

The invention constitutes a device of the type described above, in which the anode and cathode are situated so that, when the device is conducting, the current direction runs substantially along the crystal direction having the highest mobility, i.e. one of the directions [1120] or [1100]. The current direction is then at right angles to the [0001]-direction ("c-direction"). Other angles of orientation of the current direction in relation to the c-direction of the crystal are possible. This procedure produces a device with better conducting properties, lower conducting voltage, than conventional devices in which the current

runs parallel to the c-direction. These improvements are achieved by a more favourable relationship in the charge-carrying plasma obtained in the device when it is conducting, which is influenced by the electron mobility, and this relationship differs depending on the direction in which the current flows in relation to the orientation of the crystal.

Similar pn-junction structures can of course be used for other types of power devices of silicon carbide, e.g. thyristors and GTO. The use of crystal orientation in accordance with the invention can give advantages for other types of MOS-controlled bipolar devices made of silicon carbide, e.g. for ICBT, MCT or other MOS-controlled devices. Advantages with lower conducting losses are also obtained in devices of non-bipolar type such as Schottky diodes and MOSFET if the device is oriented in relation to the crystal direction so that the main current direction flows in a crystal direction with the highest mobility.

BRIEF DESCRIPTION OF THE DRAWINGS:

Figure 1 shows schematically a semiconductor diode made of anisotropic silicon carbide, with an orientation of the crystal such that the current between anode and cathode flows along a crystal direction with lower mobility (known technology).

Figure 2 shows schematically a semiconductor diode made of anisotropic silicon carbide according to the invention, with an orientation of the crystal so that the current between anode and cathode flows along a crystal direction with the higher mobility.

Figure 3 shows schematically examples of an estimated current voltage characteristic for the two cases described in Figures 1 and 2.

Figure 4 reveals a Schottky diode in which a voltage-absorbing layer has a crystal orientation in accordance with the invention.

DESCRIPTION OF EMBODIMENT

The invention is described in a number of embodiments with reference to the accompanying drawings.

An example of a semiconductor device made of silicon carbide having the properties characterized by the invention is shown in Figure 2 in the form of a semiconductor diode with a highly doped p-conducting layer 1 forming a pn-junction 2 to an n-conducting and voltage-absorbing layer 3 with low doping. The n-conducting layer 3 with low doping borders on a highly doped n-conducting layer 4 in order to create better contact with the contact 5 connected to the n-layer 4, said contact constituting the cathode of the diode. A contact 6 is connected to the p-conducting layer 1 of the diode and thus forms the anode. The arrows 7 show the main direction of the current when the diode is in conducting state. This is mentioned specifically since the current may locally have other directions in the voltage-absorbing layer, depending on the configuration of the p-conducting layer 1. The current near the edges 8 of the p-conducting layer 1, for instance, may have a different direction from the main current direction 7.

A coordinate system has also been drawn in on Figure 2, showing how the crystal structure of the silicon carbide, in this case 6H-SiC, is oriented in at least the voltage-absorbing layer 3 in the semiconductor diode. According to the coordinate system the c-direction or, according to crystallographic designations, the [0001]-direction, is oriented transversely to the main current direction 7 through the semiconductor device. This means that one of the components [1120] or [1100] in the hexagonal crystal structure will have the same direction as the main current direction 7. Angles other than 90° between the c-direction and the main current direction, such as that shown in Figure 2, are quite feasible if other conducting properties are desired in the SiC crystal than are included in one of the conducting layers of the semiconductor device.

It has been mentioned above that the voltage-absorbing layer 3 has a c-direction that deviates from the main current direction 7. It is of

course an advantage if the other layers 1, 4 are designed equivalently so that the c-direction of the crystal deviates from the main current direction through the layer in question.

The advantage of a semiconductor device in which the main current direction deviates from the c-direction is that the electrons obtain a higher mobility through the device when the crystal is oriented in accordance with the invention.

Figure 1 shows a device equivalent to a semiconductor diode according to Figure 2, according to the present state of the art. The difference between the two figures, as shown by the coordinate system in Figure 1, is that the c-direction and the main current direction 7 in the latter are parallel.

A semiconductor diode as disclosed in the invention is produced, for instance, by a method in which a silicon carbide substrate in 6H-SiC is oriented so that the c-direction of the device being produced will deviate from the main current direction in said device. The desired layers are then placed, e.g. epitaxially, on the existing substrate. These applied layers can be given a crystal orientation with optional direction.

The improvement achieved with a semiconductor device of silicon carbide having a crystal orientation in accordance with the invention is illustrated in Figure 3. A characteristic is shown there which reflects the current through a semiconductor diode as a function of the voltage. The curve indicated by a broken line reveals the ratio in a device where the c-direction of the crystal is parallel to the main current direction, whereas the strongly increased current at equivalent voltages is indicated by the whole-line curve where the strongly increased current is dependent on the strongly increased electron mobility when the crystal orientation of the silicon carbide is in accordance with the invention.

No other types of semiconductor devices are described in the example since the conducting properties corresponding to those reported for a

semiconductor diode are directly equivalent in other types of semiconductor devices made of silicon carbide in which pn-junctions with voltage-absorbing layers equivalent to that of the semiconductor device described above occur.

Figure 4 illustrates a semiconductor device with a voltage-absorbing layer 3 according to the invention, in this case exemplified by a Schottky diode. The pn-junction 2 mentioned earlier in other types of semiconductor devices is missing here. The increased electron mobility in the voltage-absorbing layer 3 offers even this type of device the improved properties touched upon for devices with pn-junctions, i.e. a better current-voltage ratio similar to that illustrated in Figure 3.

CLAIMS

1. A semiconductor device comprising at least one pn-junction (2) in which both a p-conducting layer (1) and an n-conducting layer (3) of the pn-junction (2) are in the form of doped layers of silicon carbide (SiC) and in which one of these layers consists of a low-doped voltage-absorbing layer (3), characterized in that at least the voltage-absorbing layer (3) of the pn-junction (2) exhibits a crystal structure in 6H-SiC where the [0001]-direction of the SiC crystal is oriented so that it deviates from the main current direction (7) in a current flowing through the crystal when the device is in conducting state.

2. A semiconductor device as claimed in claim 1, characterized in that the voltage-absorbing layer (3) of the pn-junction (2) exhibits a crystal structure in 6H-SiC, where the [0001]-direction of the SiC crystal is oriented at an angle of substantially 90° to the main current direction (7) in a current flowing through the crystal when the device is in conducting state.

3. A semiconductor device as claimed in claim 1 or 2, characterized in that the other conducting layer (1, 4) in the device, as well as the voltage absorbing layer (3) is also designed so that the [0001]-direction of the SiC crystal in the layer (1, 4) is oriented so that it deviates from the main current direction (7) in a current flowing through the crystal when the device is in conducting state.

4. A semiconductor device as claimed in claim 1 or 2, characterized in that the pn-junction (2) consists of a pn-junction in one of the semiconductor devices diode, bipolar transistor, thyristor, GTO, IGBT, MCT, MOSFET or MOS-controlled transistor.

5. A semiconductor device comprising at least one low-doped voltage-absorbing layer (3) of a certain conducting type, in which the layer (3) is connected directly to a metallic contact (6), characterized in that the voltage-absorbing layer (3) exhibits

a crystal structure in 6H-SiC where the [0001]-direction of the SiC crystal is oriented so that it deviates from the main current direction (7) in a current flowing through the crystal when the device is in conducting state.

1/2

Fig. 1

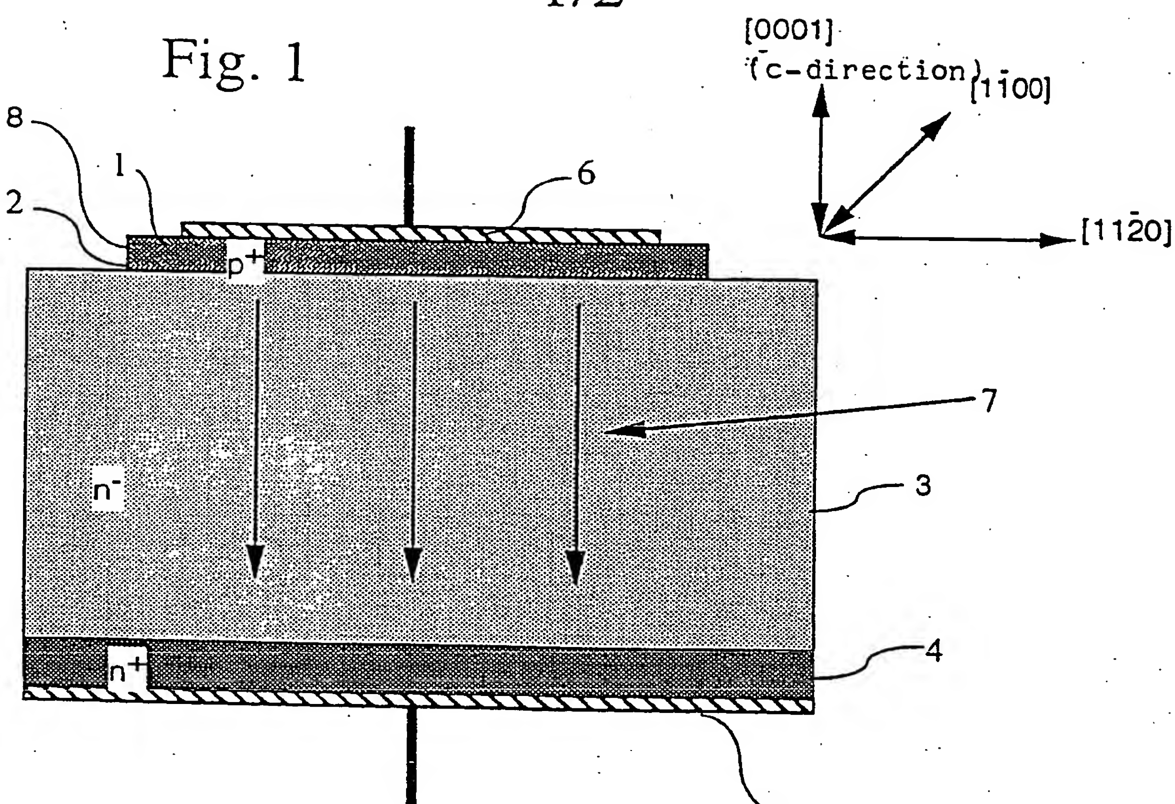
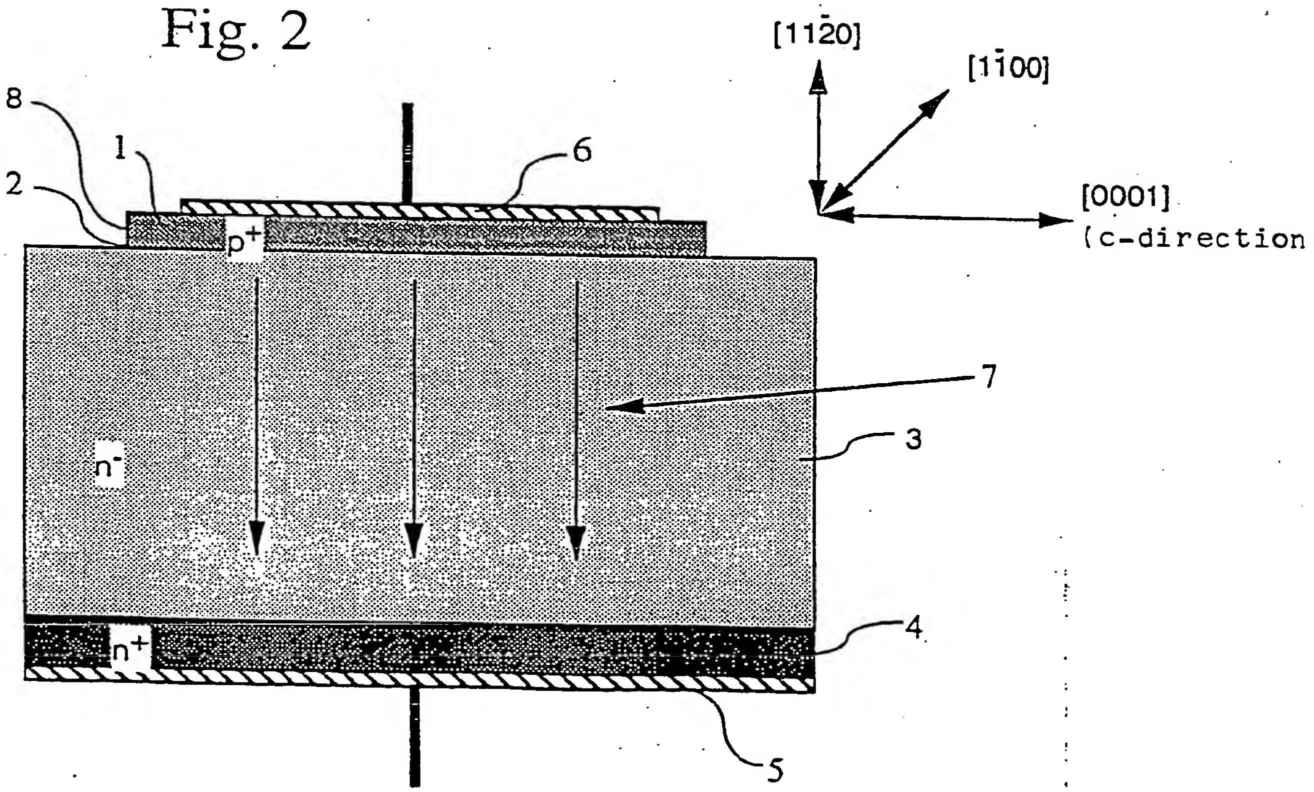

[0001]
(c-direction)
[1$\bar{1}$00]
[11$\bar{2}$0]
8
1
2
6
p+
7
n-
3
n+
4
5

Fig. 2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[1$\bar{1}$00]
[0001]
(c-direction)
8
1
2
6
p+
7
n-
3
n+
4
5

Fig. 3

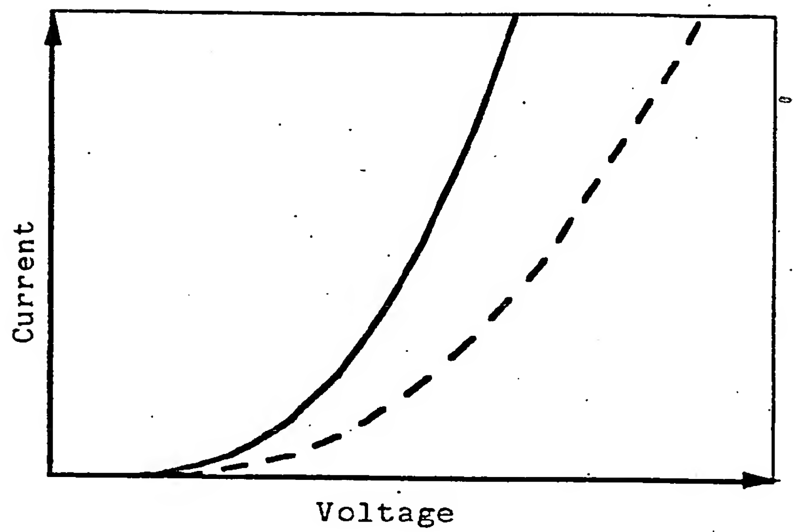
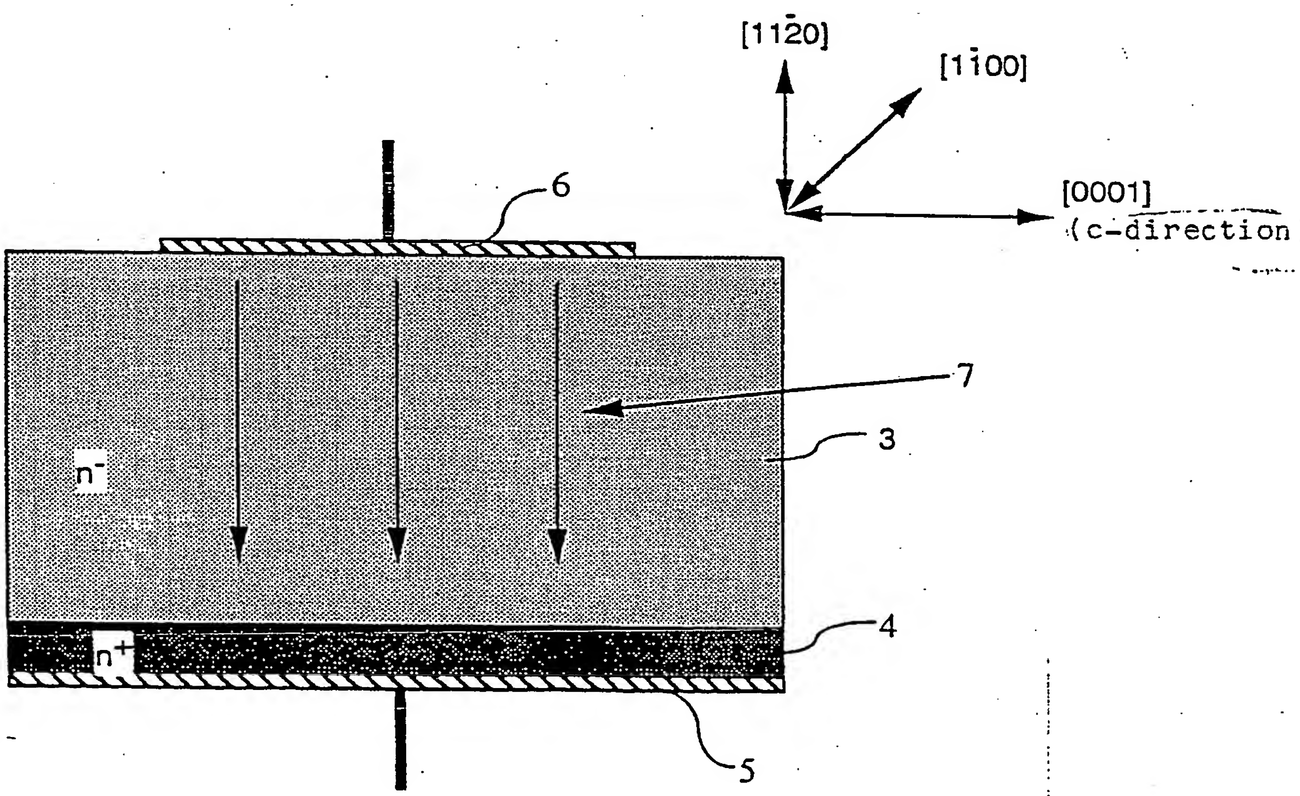


Fig. 4



INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 94/00580

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: H01L 29/24, H01L 29/04
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 4912064 (HUA SHUANG KONG ET AL), 27 March 1990 (27.03.90) --	5
A	US, A, 5243204 (AKIRA SUZUKI ET AL), 7 Sept 1993 (07.09.93), column 11, line 33 - column 13, line 22; column 17, line 5 - column 18, line 43 --	1-5
X	US, A, 5011549 (HUA-SHUANG KONG ET AL), 30 April 1991 (30.04.91) --	5

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IEEE TRANSACTIONS ON ELECTRON DEVICES, Volume 40, No 3, March 1993, M. Bhatnagar et al, "Comparison of 6H-SiC, 3C-SiC, and Si for Power Devices" page 645 - page 655	1-5

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INTERNATIONAL SEARCH REPORT
Information on patent family members

25/02/95

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Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US-A-	4912064	27/03/90	CA-A-	1317857	18/05/93
			US-A-	5011549	30/04/91
US-A-	5243204	07/09/93	DE-A-	4116563	21/11/91
			JP-A-	4025184	28/01/92
			JP-A-	4071278	05/03/92
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			US-A-	4912064	27/03/90